Neutrinos from supernovæ: experimental status and perspectives

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I discuss the state of the art in the search for neutrinos from galactic stellar collapses and the future perspectives of this field. The implications for the neutrino physics of a high statistics supernova neutrino burst detection by the network of detectors operating around the world are also reviewed.

1 Introduction

The core collapse (type II and Ib) supernovæ are spectacular events which are being studied, by using numerical simulations, since more than three decades (see e.g. [COL66], [WIL85], [BET90], [BUR90], [WIL93], [JAN94], [BUR98], [JAN96], [JAN98], [THO01], [MEZ01], [RAF01]). Despite the huge amount of physics involved in these catastrophic explosions, a sort of "supernova standard model" has been emerging in the last years ([MES98], [MEZ00b]): the inner Iron core of a massive star ($M \gtrsim 8\ M_{\odot}$) overcomes its hydrodinamical stability limit (the Chandrasekhar mass) and collapses, raising its density up to many times the nuclear density; this anomalous density produces an elastic bounce of the core, which results in a shock wave. The wave propagates through the star, loses energy in dissociating nucleons and producing neutrinos and finally stalls at ~ 200 Km from the center of the star (this means that the so-called "prompt" mechanism unavoidably fails). However, ν_e and $\bar{\nu}_e$ are absorbed on the nucleons liberated by the shock; such processes supply new energy to the wave, which is revived, ~ 500 ms after the bounce (this energy transfer is known as "neutrino heating"). The reinforced shock can propagate within the stellar matter and expel the external layers into the space (this is the so-called "delayed" mechanism). As an example of the results of a numerical simulation, Fig. 1 shows the trajectories of equal mass shells (0.01 $M_{\odot}$), the shock and the nuclear burning front in the $(time, radius)$ plane in a 13 $M_{\odot}$ model (from [MEZ00b]). After the explosion the star loses energy, mainly by neutrino emission, and cools down, forming a neutron star or a black hole.

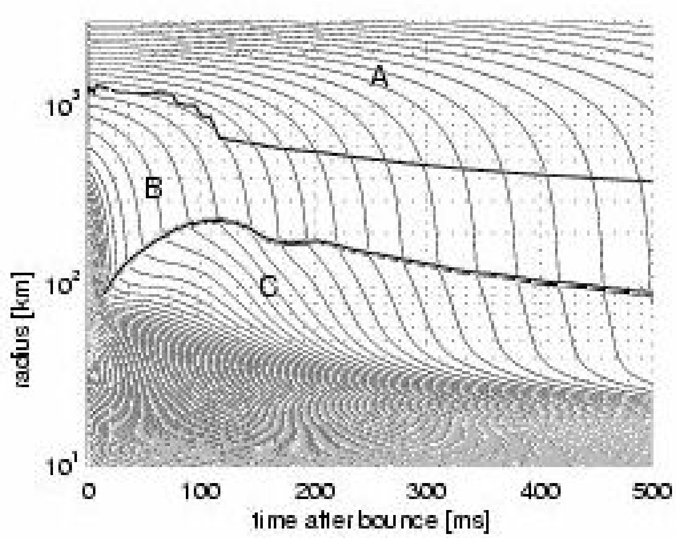

Figure 1: The trajectories of various mass shells (0.01 $M_{\odot}$), the shock (thick line) and the nuclear burning front (thin line) in the $(time, radius)$ plane. A: Silicon; B: Iron produced by infall and heating; C: Free nucleons (from [MEZ00b]).

In this general picture there are, however, still many question marks. For instance, is the neutrino heating enough to trigger the explosion or some other energy transfer mechanism is needed ? Do the convection of the stellar matter, the star rotation and/or the star magnetic field play important roles in enhancing the energy transfer ? Is the behaviour of the nuclear matter at a density $\sim 10^{14}$ g cm^{-3} really well understood and the neutrino transport inside such a highly degenerate matter treated with sufficient accuracy ? Is the spherical symmetry of the explosion largely violated, as the detection of polarized light and boosted ^{56}Ni nuclei in the SN1987A remnants [WHE00] seems to indicate ? Is the residual of the explosion a neutron star or a black hole ? Is there a sort of "threshold progenitor mass", which separates these two different destinies ?

These are only few of the various open questions which could be addressed, at least partially, by the observation of a neutrino burst from a galactic supernova ([PRA01], [TOT98a]). Many features of the collapse mechanism are indeed imprinted in the neutrinos released during the explosion. At the same time, a galactic supernova explosion would give particle physicists the opportunity to explore the neutrino properties on scales of distance up to $\sim 10^{17}$ Km, of time up to $\sim 10^5$ years and of density beyond that of the nuclear matter.

Here I will focus on the real time detection of supernova neutrino bursts, without considering the ideas and techniques developed to search for relic neutrinos from past supernovæ.

2 Supernova Neutrino Bursts

A supernova explosion releases $\sim 2 \div 4 \times 10^{53}$ ergs of gravitational binding energy. The kinetic energy of the expelled matter is lower by about two orders of magnitude and the energy emitted in electromagnetic radiation and gravitational waves is even less; then, the bulk of the energy is released in the form of neutrinos.

A first ν_e burst is emitted during the infall stage of the collapse (*"infall burst"*), since the high density of matter makes the electron capture by proton:

$$e^- + p \rightarrow \nu_e + n \tag{1}$$

very efficient. However, this neutrino emission does not continue indefinitely, since at a density $\sim 10^{12}$ g cm^{-3} the neutrinos are trapped in the stellar core and go into equilibrium with matter via the inverse process:

$$\nu_e + n \rightarrow e^- + p \tag{2}$$

Immediately after the core bounce, also neutrinos of other flavours begin to be produced, via nucleonic bremsstrahlung and pair annihilation processes as:

$$e^+ + e^- \rightarrow \nu_x + \bar{\nu}_x \tag{3}$$

The neutrinos are trapped in a region (the *"neutrinosphere"*) whose size is different for different neutrino flavours. Neutrinos produced at a distance from the center larger than the neutrinosphere radius can freely escape to infinity, while neutrinos produced within this sphere remain trapped. Electron neutrinos and antineutrinos interact with matter via neutral and charged current processes (as (2) or $\bar{\nu}_e + p \rightarrow e^+ + n$), while non-electron neutrinos and anti-neutrinos (from now on, collectively indicated with "ν_x") interact only via neutral currents. Therefore, the ν_x are less tightly coupled with matter than ν_e and $\bar{\nu}_e$ and a higher matter density is needed to trap them. Moreover, since the mantel is richer in neutrons than in protons (because of the (1) process), the ν_e are more strongly coupled than the $\bar{\nu}_e$. As a result, the neutrinosphere radius is maximum for ν_e and amounts to ~ 70 Km for ν_e, to ~ 50 Km for $\bar{\nu}_e$ and to ~ 30 Km for ν_x. The larger the neutrinosphere radius, the lower the mean neutrino energy (a deeper neutrinosphere corresponds to a higher temperature); so, the neutrino mean energies are expected to be (see e.g. [JAN93]):

$$\langle E_{\nu_e} \rangle \approx 10 \div 13 \text{ MeV} \tag{4}$$
$$\langle E_{\bar{\nu}_e} \rangle \approx 14 \div 17 \text{ MeV} \tag{5}$$
$$\langle E_{\nu_x} \rangle \approx 22 \div 27 \text{ MeV} \tag{6}$$

When the shock crosses the ν_e neutrinosphere, an intense burst of ν_e is produced, since the efficiency of the (1) process is abruptly enhanced by the large number of protons liberated by the shock (*"neutronization burst"*). The infall and neutronization bursts are very rapid (~ 10 ms); the ν_e energy is ~ 10 MeV and the total released energy is $\lesssim 10^{52}$ erg.

After the neutronization stage, the ν_e luminosity rapidly decreases, while the luminosities of other flavour neutrinos increase. The neutrinos are now produced mainly via the (3) process and the higher rate of ν_e, $\bar{\nu}_e$ production is compensated by the larger coupling of these neutrinos with matter. As a result, at the end of the neutrino diffusion inside the mantle the energy is practically equally distributed between the various neutrino flavours ($\sim 5 \times 10^{52}$ ergs for each neutrino type). This final stage (*"cooling"*) requires ~ 10 s and takes away $> 99\,\%$ of the gravitational energy of the star.

Fig. 2 shows an example of the neutrino luminosities as a function of time after the bounce [LIE01]. Note the ν_e neutronization peak, the sharp rise (tenths of ms) of all flavour luminosities and the much longer trailing edge of all neutrino signals.

The neutrino energy spectra at the time of decoupling reflect the fact that, inside the core, they are in equilibrium with matter; so, thermal (Fermi-Dirac) or quasi-thermal spectra are obtained by numerical simulations; an example is shown in Fig. 3 (from [TOT98a]).

The general features of neutrino spectra and luminosities are rather similar in the various simulations; some of them (average $\bar{\nu}_e$ energy, duration of the burst, energy emitted in $\bar{\nu}_e$ etc.) were also confirmed by the observation of SN1987A neutrinos. In the rest of this paper I will refer to the [BUR92] paper as a benchmark for computing the expected neutrino signals in various detectors. Other models predict harder spectra (expecially for ν_x), so that the expected fractions of the various types of neutrino events can change by many percent, mainly for the ν_x-induced neutral current reactions.

3 Supernova neutrino reactions

The detection of supernova neutrinos requires their conversion into a charged lepton or the emission of some other particles (essentially γ's or neutrons) which can be efficiently observed. An "ideal" reaction should be sensitive to all flavours of neutrinos and preserve all informa-

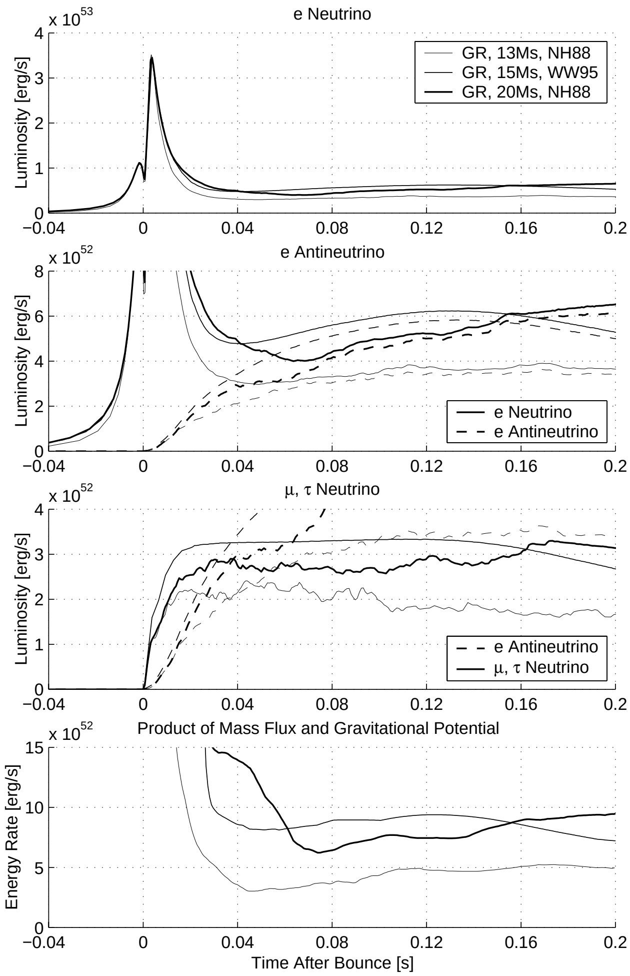

Figure 2: Luminosities for all kind of neutrinos as a function of time after the bounce (first three graphs). In any graph three different curves are shown, each one corresponding to a different explosion model. The last graph shows the energy production rate, closely similar to the neutrino luminosity (from [LIE01]).

tion on neutrino energy spectrum, timing, direction and type; however, usually only a part of this information can be derived by a single process and then a combined observation by detectors based on different technologies is fundamental to obtain a comprehensive picture of the neutrino burst properties.

Here I briefly review the reactions employed in the supernova neutrino detection, which fall in four main cathegories.

- **Charged currents on nucleons (CCn(p)).** These processes are useful only for ν_e and $\bar{\nu}_e$, because the ν_x energies are under the threshold for charged leptons (μ and τ) production. Target materials containing free neutrons are not available;

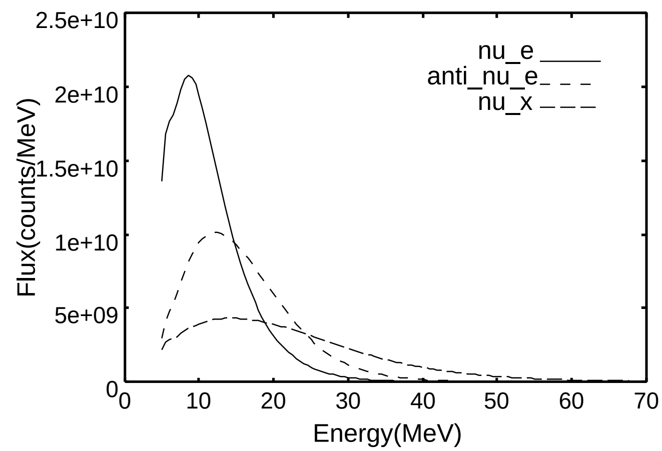

Figure 3: Neutrino and antineutrino energy spectra; ν_x indicates non-electron neutrinos or antineutrinos (from [TOT98a]).

then, one is left with the inverse-beta reaction:

$$\bar{\nu}_e + p \rightarrow e^+ + n \tag{7}$$

This reaction is the most interesting one in proton-rich targets, like water or hydrocarbonic scintillators. Its cross section is proportional to the square of the neutrino energy, but it is usually written in the following form [BAH89]:

$$\sigma = 8.5 \times 10^{-44} \ \left(E_{e^+}\,(\mathrm{MeV})\right)^2 \ \mathrm{cm}^2 \tag{8}$$

which contains the directly measurable e^+ energy, related to the $\bar{\nu}_e$ energy by the formula $E_{e^+} \approx E_{\bar{\nu}_e} - m_n + m_p = E_{\bar{\nu}_e} - 1.293$ MeV. A further 1.022 MeV energy can be detected because the positron annihilates with an electron, producing a pair of 0.511 MeV photons. The neutron emitted in the process (7) can be thermalized and captured by a proton, forming a Deuterium nucleus and releasing the binding energy as a 2.2 MeV γ (from now on, $\gamma_{2.2}$). In liquid scintillators the average moderation time is $\sim 10\ \mu$s and the average capture time is $\sim 180\ \mu$s. The detection of $\gamma_{2.2}$ is a further signature of the (7) reaction and can be an important tool to separate the (7) positrons from the products of other reactions. The threshold for the process (7) is 1.8 MeV, a value which cuts off only a small fraction ($\lesssim 5\,\%$) of the $\bar{\nu}_e$ spectrum. All SN1987A neutrinos observed by Kamiokande II [KAM87], IMB3 [IMB87] and Baksan [BAK87] are generally believed to be $\bar{\nu}_e$, detected via the (7) process. The reaction (7) has only a weak dependence on the neutrino incoming direction [VOG99]: the average value of the cosine of the angle between

$\bar{\nu}_e$ and e^+ varies from ≈ -0.03 to ≈ 0.1 in the supernova neutrino energy range.

- **Elastic scattering on electrons (ES).** This reaction is possible, in principle, for all kind of neutrinos; however, ν_e and $\bar{\nu}_e$ interact with electrons via charged (with different couplings) and neutral currents, while ν_x interact only via neutral currents. The ν_e have the highest cross section:

$$\sigma_{\nu_e\, e} = 9.2 \times 10^{-45}\ E_{\nu_e}(\mathrm{MeV})\ \mathrm{cm}^2. \tag{9}$$

and the following cross section hierarchy holds:

$$\sigma_{\nu_e\, e} \approx 3\, \sigma_{\bar{\nu}_e\, e} \approx 6\, \sigma_{\nu_x\, e} \tag{10}$$

The number of ES events expected in a detector is much lower than that expected for (7) reactions because of the lower multiplicative coefficient and of the linear dependence of the cross section (9) on the neutrino energy. However, the angular distribution of the ES electrons is strongly peaked around the neutrino incoming direction, with an opening angle $\theta_{\nu_e,e} \sim (m_e/E_{\nu_e})^{1/2}$ [BAH89]; the ES is then a useful reaction for determining the supernova direction. The Kamiokande [KAM96], Super-Kamiokande [BLA01] and SNO [WAL01] experiments detected thousands of ES events induced by solar neutrinos. Note that the ratio between the number of (7) and (9) events is sensitive to the neutrino energy spectra and is then an important tool in discriminating between various supernova models [SCH88].

- **Charged currents on nuclei (CCN).** Again, only ν_e and $\bar{\nu}_e$ can interact via charged current reactions. A general feature of CCN reactions is a relatively high cross section, in some cases competitive with that of the CCn reactions for neutrino energies $\gtrsim 20 \div 30$ MeV. These reactions are followed by the $\beta^{\pm}$-decay ($\tau \sim 20$ ms) of the products nuclei, so that they have, in principle, a very clean signature. However, their practical application is usually strongly limited by the high threshold (~ 15 MeV for interactions with C or O nuclei), which cuts off the most part of the ν_e, $\bar{\nu}_e$ spectrum.

A very important exception is the Deuterium, which can be disintegrated by ν_e, $\bar{\nu}_e$ via the processes (for recent evaluations of the cross sections see [BUT01], [NAK01]):

$$\nu_e + d \rightarrow e^- + p + p \tag{11}$$
$$\bar{\nu}_e + d \rightarrow e^+ + n + n \tag{12}$$

The thresholds for reactions (11) and (12) are respectively 1.44 MeV and 4.03 MeV; both these values are well below the average ν_e, $\bar{\nu}_e$ energy. The angular distributions of both the processes have the form $d\sigma/d\Omega \propto 1 - a\,(E_\nu)\cos(\theta)$, where θ is the angle between ν_e ($\bar{\nu}_e$) and e^- (e^+) and $a\,(E_\nu)$ is an energy-dependent coefficient. In the supernova neutrino energy range, $a\,(E_\nu)$ is nearly costant at $\approx 1/3$ for ν_e, while for $\bar{\nu}_e$ it is proportional to E_ν and ranges from $\approx 1/3$ at $E_\nu = 0$ to ≈ 0 at $E_\nu = 50$ MeV. The recent measurement of the solar neutrino flux by the SNO experiment [WAL01] via the (11) process showed that such reaction can be succesfully employed for detecting low energy neutrinos and that its contribution can be statistically separated by that due to ES reactions.

An other interesting CCN reaction is:

$$\nu_e\ +\ ^{40}Ar \rightarrow\, ^{40}K^*\ +\ e^- \tag{13}$$

which can take place in Liquid Argon detectors [ORM95]. This reaction has a 5.885 MeV threshold and is accompanied by the $^{40}K^*$ de-excitation to the ground state, which releases a 5 MeV γ. The cross section of this reaction overcomes that of the (7) process for $E_{\nu_e} \gtrsim 20$ MeV.

- **Neutral currents on nuclei (NC).** As one can argue from the previous discussion, the detection of ν_x is the most challenging goal of the supernova neutrino detectors. Despite the larger difficulties, the detection of ν_x is extremely important, not only for astrophysics, but also for particle physics, because of the opportunity to set stringent limits on the masses of non-electronic neutrinos (this point will be examined in section 5.4). Two kinds of possible processes were suggested: the excitation and subsequent de-excitation of a nuclear level, accompanied by the emission of a photon, and the knocking off of a neutron. Note that none of these reactions is sensitive to the neutrino energy or direction, since the energy of the de-excitation photon is set by the nuclear level, the neutron recoil can not be measured and the neutron and photon emissions are essentially isotropic. However, the neutrino arrival time can be measured.

Neutrinos can excite ^{12}C to a 15.1 MeV level (the de-excitation photon will be indicated, from now on, by $\gamma_{15.1}$). The cross sections for neutrino-Carbon reactions were measured by the LAMPF [LAM92], Karmen [KAR93] and LSND [LSN97] collaborations and the experimental values were in agreement with theoretical calculations [FUK88]. Because of the high threshold (15.1 MeV), this NC process is a good selector of ν_x, whose spectrum is harder than that of ν_e, $\bar{\nu}_e$.

Neutrinos can also excite ^{16}O via various anelastic processes with emissions of protons (or neutrons) and γ's, with a total photon energy between 5 and 10 MeV [LAN96]. As for reactions on Carbon, only the more energetic ν_x can efficiently excite ^{16}O nuclei because of the high energy threshold.

The Deuterium nucleus can be disintegrated by neutrinos of all flavours via the NC process:

$$\nu_x + d \rightarrow \nu_x + n + p \tag{14}$$

The cross section for reaction (14) was computed by many authors (e.g. [BUT01], [NAK01]) and is competitive with that of (7) process; the threshold is 2.2 MeV, so that also ν_e and $\bar{\nu}_e$ can efficiently break-up the Deuterium nuclei. (The process (14) can indeed give a flavour-independent measurement of the solar neutrino flux and was originally suggested having such a goal in mind.)

Finally, during the last years some theoretical calculations (e.g. [CLI94]) pointed out that the cross sections for neutron knocking off from certain heavy nuclei (Ca, Na, Pb ...) are large ($\sim 10^{-42}$ cm^2) and steeply increasing at energies $\gtrsim$ 20 MeV, so that the more energetic ν_x could be efficiently selected. The use of chemical compounds of high solubility in water, as $Pb\,(ClO_4)_2$, has also been suggested to combine the high value of the CCN and NC neutrino cross sections on high-Z nuclei with the experimental advantages offered by the water Čerenkov technology [ELI00]. By now these cross section calculations have no experimental support, but proposed new facilities, like **ORLaND** at Oak Ridge National Laboratory [MEZ00a], should provide some measurements of neutrino-nucleus cross sections of interest in supernova neutrino detection.

To summarize, Fig. 4 shows the cross sections (in nb) for CCp, ES, CC and NC on Carbon processes and Fig. 5 the cross sections for the various neutrino reactions on Deuterium and Oxygen.

4 Present supernova neutrino detectors

4.1 General considerations

The supernovæ are very rare events: the expected rate of galactic stellar collapses is $\sim 1/20 \div 40$ years ([VAN93], [TAM94]) (note that this is a, so to say, "unlucky" number: it is too low to give a good chance of success to an experiment with an operating life of $\sim$ 10 years and, at the same time, is too high to make a real time detection of a supernova neutrino burst a hopeless dream). Moreover,

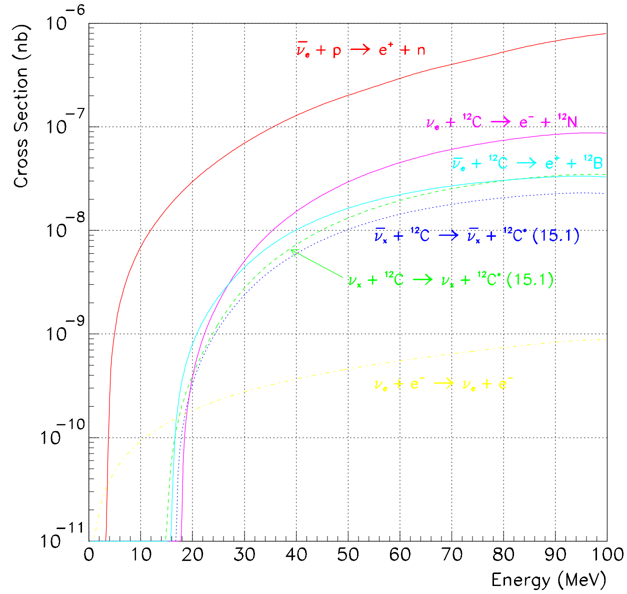

Figure 4: Cross sections for CCp, ES, CC and NC on Carbon processes.

the supernova neutrinos have energies of tenths of MeV or less, with low cross sections (as discussed above) and, finally, a supernova has (at least can have[a]) a bright optical flare and releases radiation in other forms than neutrinos. These three points set the fundamental guidelines in designing a good supernova neutrino detector:

1) the detector must have a mass $\gtrsim 10^3$ tonn of active material. Such material must be cheap, robust and possibly not polluting;
2) the detector must be located underground, to reduce the cosmic ray induced background, and possibly in a low radioactivity environment;
3) the detector must have a very high duty cycle (in principle it should be always active) and an operating life of at least $\sim$ 10 years;
4) the detector must be equipped with electronics and acquisition systems well suited to perform a real time neutrino detection, with good accuracies in absolute ($\lesssim$ 1 ms) and relative ($\lesssim 1\ \mu$s) timing and (if possible) good angular and energy resolutions. The energy threshold should not exceed $\sim$ 10 MeV.

I now review the presently active neutrino detectors and discuss how (and whether) the requests listed above are

[a] The optical flare can be absent because the explosion "fizzles" or because the supernova is in a sky region optically obscured by the halo luminosity or the cosmic dust.

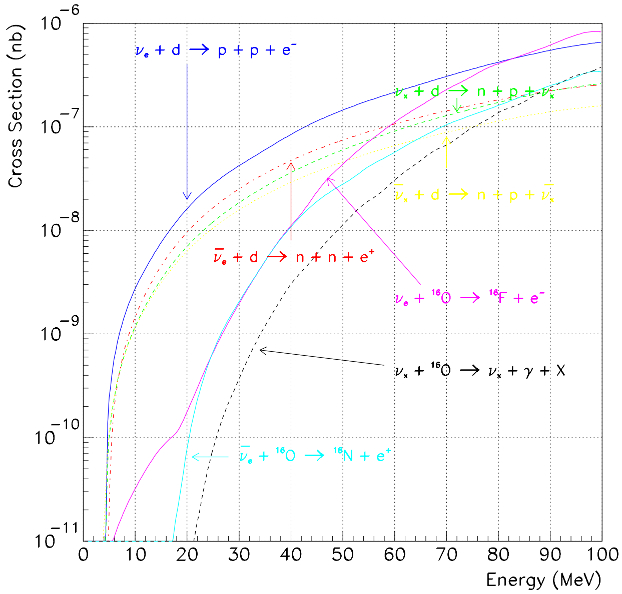

Figure 5: Cross sections for neutrino reactions on Deuterium and Oxygen. The shoulder at low energies of the ν_e-Oxygen cross section comes from the contribution of ^{18}O ($< 0.1\,\%$ of isotopic composition of the normal Oxygen).

satisfied. Note that most of these detectors were build having in mind also other physics goals, as the detection of solar and atmospheric neutrinos, the search for magnetic monopoles and proton decay, the observation of high energy cosmic rays etc.

4.2 Scintillation detectors

Scintillation detectors use large masses ($\sim 10^3$ tonn) of high transparency mineral oils (CH_n, $n = 1, 2$), segmented in hundreds of individual counters or enclosed in a container and observed by hundreds of PMTs at the boundary of the active volume. The scintillation detectors are mainly sensitive to $\bar{\nu}_e$ via the process (7); a contribution of $3 \div 6\,\%$ of the total number of events is expected from the NC on Carbon reactions and even lower contributions from ES and CC on Carbon processes. The scintillation detectors have a larger light yield and a better energy resolution than the water Čerenkov detectors; then, they are sensitive to the $\gamma_{2.2}$.

The **LVD** [LVD92] (**L**arge **V**olume **D**etector) experiment, shown in Fig. 6, is presently the largest operating liquid scintillation detector in the world. This detector is located in the Hall "A" of the Laboratory Nazionali del Gran Sasso (LNGS), in the central Italy, at an average depth of 3100 m.w.e.. After many years of operation

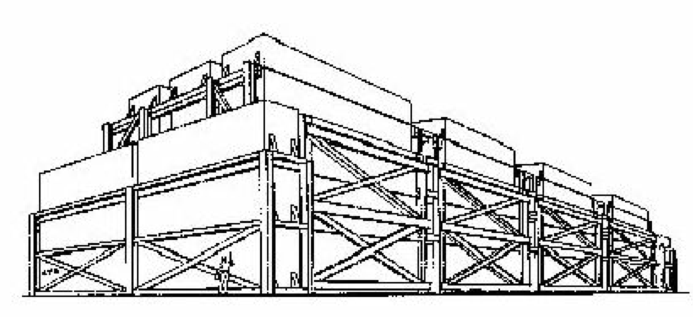

Figure 6: The LVD experiment.

with ~ 600 tonn of liquid scintillator, LVD reached this year its final active mass of $\approx 10^3$ tonn, organized in 840 counters ($1 \times 1 \times 1.5$ m^3 each) interleaved with Streamer Tubes for cosmic muons tracking [VIG01]. This structure is partially self-shielded, with the internal counters ($\sim 30\,\%$ of the total) subject to a lower radioactive background than the external ones.

The **MACRO** ([MAC92], [MAC98a]) (**M**onopole **A**strophysics and **C**osmic **R**ay **O**bservatory) experiment, also located in the LNGS (Hall "B") and recently ended (December 2000), with 570 tonn of active mass had a sensitivity similar to that of LVD. This detector was equipped with 476 very long counters (≈ 12 m each), deployed in horizontal and vertical layers.

Table 1 compares the LVD and MACRO properties in neutrinos from stellar collapse detection. The upper part of the table shows the expected number of events in these two detectors from a supernova at the Galactic Center (distance 8.5 Kpc) and the lower part compares their performances (resolution, energy threshold E_{thr} etc.) at supernova neutrino energies.

A third scintillation detector, the **Baksan** observatory [BAK98], equipped with 200 tonn (fiducial volume) of liquid scintillator, has been searching for galactic stellar collapses since more than 20 years. During 1987 this detector recorded a 5 event burst which was generally attributed to neutrinos from SN1987A [BAK87].

Two liquid scintillation detectors of the "egg-container" type should go on-line soon, **Borexino** [CAD00] in the LNGS (Hall "C") and **Kamland** [SVO01] in the Kamioka mine (Japan). Borexino has a multi-shielding structure, with an internal fiducial volume of 300 tonn of liquid scintillator; Kamland has an active volume of ≈ 1000 tonn, surrounded by an external buffer of mineral oil and liquid scintillator, used as veto for radioactivity and cosmic ray muons. Both these detectors were designed to perform a real time detection of very low energy neutrinos (solar neutrinos for Borexino and reactor antineutrinos for Kamland) and

Table 1: Upper part: expected number of events in LVD (10^3 tonn) and MACRO from a supernova at the Galactic Center. Lower part: comparison between the LVD and MACRO performances at $E = 10$ MeV. ("E" and "I" indicate the external and internal LVD counters.)

Number of expected events				
	LVD		MACRO	
	Events	(%)	Events	(%)
$\bar{\nu}_e + p$	296	93.0	198	94.7
$\nu_e + e$	5	1.6	3	1.4
$\bar{\nu}_e + e$	1	0.3	< 1	< 0.5
$\nu_x + e$	3	0.95	2	0.96
$\nu_e + C$ (**CC**)	≈ 1	0.3	< 1	< 0.5
$\bar{\nu}_e + C$ (**CC**)	≈ 1	0.3	< 1	< 0.5
$\nu_x + C$ (**NC**)	11	3.5	4	1.9
Total on p	296	93.0	198	94.7
Total on e	9	2.8	$5 \div 6$	$2.4 \div 2.9$
Total on C	13	4.1	$5 \div 6$	$2.4 \div 2.9$
Total	318	100	209	100

Performances		
	LVD	MACRO
E_{thr} (**MeV**)	7 (E), 4 (I)	7
$\frac{\sigma_E}{E}$ (%)	15	10
σ_t (ns)	12.5	1
$\epsilon_{\gamma_{2.2}}$ (%)	70	25
$\epsilon_{\gamma_{15.1}}$ (%)	50	30

are then characterized by an extremely low radioactivity background (the ^{238}U and ^{232}Th contaminations are at the level of 10^{-16} g/g). An other interesting feature of these detectors is that, having a large homogeneous active volume, they are well suited to detect high energy photons, particularly $\gamma_{15.1}$.

4.3 Water Čerenkov detectors

Water Čerenkov detectors use large volumes of highly purified water, equipped with an array of inward-looking PMTs to detect the Čerenkov light produced by relativistic charged particles. The energy and direction of the particles can be inferred by the total amount of collected light and by the pattern of illuminated phototubes. The Čerenkov detectors have a continuous active volume and are self-shielded, i.e. the inner part of the detector is shielded from the external radioactivity background by the outer one; a fiducial volume can then be defined. The water Čerenkov experiments are mainly sensitive to the (7) process, with few per cent contributions from other reactions. The Kamiokande II and IMB3 detectors, which recorded the well established burst of neutrinos from SN1987A, were both water Čerenkov experiments.

Figure (7) shows the **Super-Kamiokande** detector [SKA98a], a 50 kton water Čerenkov experiment located in the Kamioka mine (Japan), at a depth of ≈ 2700 m.w.e. (from now on SK). This detector has a

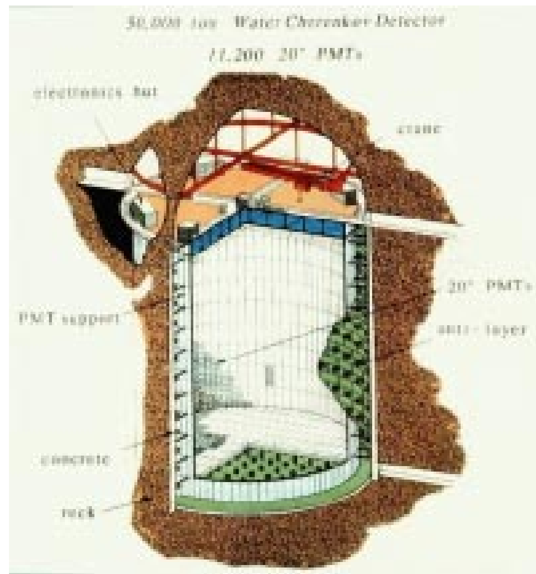

Figure 7: The Super-Kamiokande experiment.

fiducial volume for supernova neutrinos of 32 kton and is equipped with 11146 20 inch PMTs, with a photocathodic coverage of 40 % of the total surface. An external buffer of water, equipped with ≈ 1800 8 inch PMTs, is used as a veto. Energy and angular resolutions at 10 MeV are ≈ 16 % and 27°; the energy threshold is ≈ 6 MeV.[b] Table 2 shows the expected number of events in SK for a type II supernova at the Galactic Center.[c]

[b] On 12 November 2001 a severe accident destroyed about half of the Super-Kamiokande PMTs. The plan of the collaboration is to refill the whole detector and to equip it with the surviving PMTs; this should degrade the quoted resolutions by about a factor $\sqrt{2}$ and raise the energy threshold up to ~ 8 MeV. However, the number of events expected from a galactic stellar collapse should be reduced by only few percent.

[c] Note that the benchmark model [BUR92] predicts no events from ^{16}O excitation in SK: this is due to the fact that the cross sections for these processes were recently evaluated in detail [LAN96] and that the average ν_x energy in this model is $\langle E_{\nu_x} \rangle \approx 16$ MeV. Other calculations, based on harder ν_x spectra ($\langle E_{\nu_x} \rangle \approx 25$ MeV),

Table 2: Expected number of events in SK (32 kton of fiducial volume) from a supernova at the Galactic Center.

Reaction	**Events**	**Fraction (%)**
$\bar{\nu}_e + p$	7349	95.9
$\nu_e + e$	107	1.4
$\bar{\nu}_e + e$	23	0.3
$\nu_x + e$	69	0.9
$\nu_e + O$	50	0.65
$\bar{\nu}_e + O$	63	0.85
Total on e	199	2.6
Total on O	113	1.5
Total on p	7349	95.9
Total	7661	100

4.4 Heavy water Čerenkov detectors

SNO (**S**udbury **N**eutrino **O**bservatory) [SNO00] (Fig. 8) is a large heavy water Čerenkov detector, located in the Creighton mine (Canada), at a depth of 6010 m.w.e.. The experiment is based on 1000 tonn of D_2O, surrounded by an external shield of 5000 tonn of light water (the inner 1400 tonn of water can also be used for supernova neutrino detection). The heavy water is looked by > 9000 PMTs and the light water by ≈ 2000 PMTs. The energy and angular resolutions at supernova neutrino energies are close to that of SK; the energy threshold is ~ 4 MeV.

The simultaneous presence of heavy and light water makes SNO a very promising experiment for detecting supernova neutrinos, since it has a good sensitivity to neutrinos of all flavours. This versatility comes mainly from the low-threshold Deuterium break-up reactions (11), (12) and (14). To have a good efficiency in capturing the neutron emitted in (14), a $NaCl$ doping will be added to the heavy water. The Chlorine has a high cross section for neutron capture; its de-excitation (with a time constant of 4 ms) releases a ≈ 8.6 MeV electromagnetic cascade. The capture efficiency with the planned $NaCl$ doping is $\epsilon \approx 83\,\%$ [WAL01]. Note that the γ background is a potentially serious problem for the NC measurement, since what a neutrino disintegrates, a γ disintegrates too. The measured U and Th radioactive contaminations [MDO00], at a level of few times 10^{-14} g/g, indicate that the NC reactions can be observed, even for solar neutrinos, with small systematic uncertainties.

predict some hundreds of these events in SK for a supernova at the Galactic Center [BEA98a].

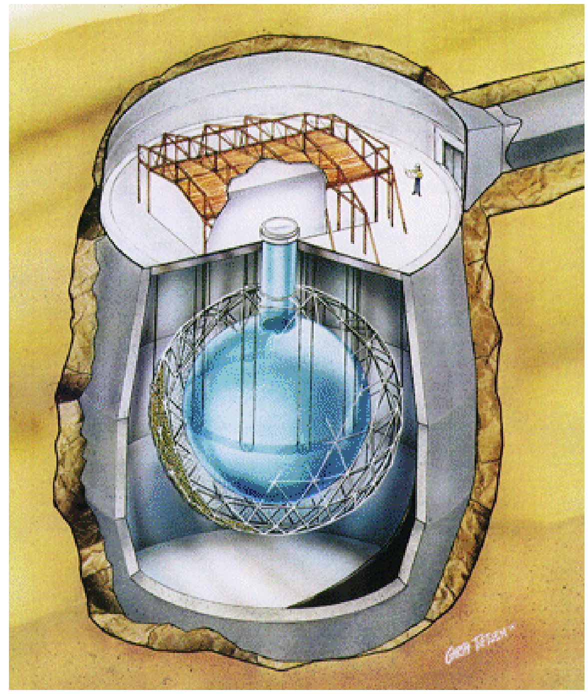

Figure 8: The SNO experiment.

Table 3 shows the expected number of events in SNO for a supernova at the Galactic Center.[d]

4.5 Other detectors

ICARUS

ICARUS (**I**maging of **C**osmic **A**nd **R**are **U**nderground **S**ignals) is a modular Liquid Argon projection chamber; the first module, with a sensitive mass of 600 tonn, will be installed soon in the LNGS (Hall "C"). The Liquid Argon is mainly sensitive to ν_e, via the (13) process; ~ 40 ν_e events could be detected in one ICARUS module for a supernova at the Galactic Center, with reasonable chances to have a good signature of the infall-neutronization burst. Some other ($\sim$ 10) events are expected by ES reactions induced by neutrinos of all flavours [ICA01].

High Energy Neutrino Telescopes (HENTs)

HENTs (**AMANDA** and **Baikal** (already on-line), **NESTOR**, **ANTARES** and **NEMO** (under development)) are arrays of hundreds of Optical Modules (OM), deployed in long strings ($\sim$ Km) in deep sea or antarctic ice. These detectors look at energetic cosmic ray

[d] As already observed for SK, the [BUR92] model does not take into account NC reactions on Oxygen; more recent papers [BEA98b] predict ≈ 60 events of this type in SNO for a supernova at the Galactic Center.

Table 3: Expected number of events in SNO from a supernova at the Galactic Center.

Reaction	**Events**	**Fraction (%)**
$\bar{\nu}_e + p$	446	39.8
$\nu_e + e$	26	2.3
$\bar{\nu}_e + e$	8	0.7
$\nu_x + e$	12	1.1
$\nu_e + O$	$4 \div 5$	$0.36 \div 0.45$
$\bar{\nu}_e + O$	$5 \div 6$	$0.45 \div 0.54$
$\nu_e + d\ (CC)$	113	10.1
$\bar{\nu}_e + d\ (CC)$	201	17.9
$\nu_e + d\ (NC)$	43	3.8
$\bar{\nu}_e + d\ (NC)$	44	3.9
$\nu_x + d\ (NC)$	224	20.0
NC on D	311	27.7
CC on D	314	28.0
CC on O	10	0.9
Total on e	46	4.1
Total on p	446	39.8
Total on D_2O	645	57.5
Total on H_2O	476	42.5
Total	1121	100

muons and have an energy threshold in the GeV range; however, they have some sensitivity to a galactic supernova explosion because of a collective effect, the excess of single counting rates produced in all OMs by a stream of thousands of low energy positrons concentrated in a short time [HAL94]. A supernova trigger based on this idea is active in **AMANDA** (**A**ntartic **M**uon **A**nd **N**eutrino **D**etector **A**rray) [NEU01]; the experimental measurements of environmental background and PMT noise and the Monte Carlo calculations of the expected signal [HAL96] showed that AMANDA can detect galactic supernova explosions with a statistical significance $\geq 6\ \sigma$ above the average counting rate.

Radiochemical detectors

The radiochemical detectors, like **GNO**, **SAGE** and **Homestake**, are time-integrated detectors, sensitive to solar ν_e's via CC reactions. The active material is periodically ($T \sim 1$ month) extracted to look for isotopes produced by the CC reactions. Their value as supernova detectors is clearly rather limited, because no information can be extracted about timing, energy and direction of neutrinos. However, in case of a nearby supernova, some ν_e events should be recorded by these detectors and a prompt extraction could allow to determine whether a statistically significant increase of the counting rate was observed in the relevant period.

4.6 Ideas for "far" future projects

The experimental success of detectors like SK or AMANDA stimulated some ideas to extend the technologies employed in these experiments to much larger scales. The goals of such projects is to gain order-of-magnitudes with respect to the present sensitivities on proton decay search, detection of solar, atmospheric and high energy neutrinos etc.; moreover, the long baseline and neutrino factory projects demand very large and refined neutrino detectors.

Here I look at some of these ideas from the point of view of the supernova neutrino detection.

UNO

UNO (**U**ltra underground **N**ucleon decay and neutrino **O**bservatory) is a project for a large scale Water Čerenkov detector. The idea is to reach a total mass of 650 kton of water, organized in three compartments, $60 \times 60 \times 60\ \mathrm{m}^3$ each, arranged in a linear structure. This configuration seems the most promising (in respect, e.g., with a cubic shape) in terms of fiducial volume, duty cycle, mechanical stability etc. The fiducial volume should be 445 kton (14 times that of SK). The total number of PMTs is ~ 60000 (with a photocatodic coverage of 40 % in the central section and 10 % in the side ones) and the estimated cost is 500 M\$. A galactic stellar collapse should produce $\sim\ 10^5\ e^+$ events in UNO, but also a supernova in the Andromeda galaxy (the closest to the Milky Way, at a distance of 700 Kpc) should be observable in this detector, with an expected signal of few tenths of events. The sensitivity to extra-galactic supernovæ is an important quality factor, since the rate of stellar collapses in the Local Group is expected to be several times higher than that in our galaxy; this gives a much higher chance of success to an experiment capable to look beyond the Milky Way [JUN00].

SNBO/OMNIS, LAND

SNBO/OMNIS (**S**upernova **N**eutrino **B**urst **O**bservatory; the **O**bservatory for **M**ultiflavour **N**eutrinos from **S**upernovæ) ([CLI90], [SMI97]) and **LAND** (**L**ead **A**stronomical **N**eutrino **D**etector) [HAR96] are projects of large mass ($\sim 10^4$ tonn) detectors, made of low-cost, high-Z materials ($NaCl$, Fe and/or Pb), whose main goal is the observation of NC events from a supernova neutrino burst. The neutrons emitted in knocking-off NC processes should be observed by long ^6Li or ^{10}B detectors or by Gd-doped liquid scintillation counters, interspaced within the target materials. These detectors should record, in case of a galactic supernova, ~ 1000 NC events, mainly induced by ν_x's. The OMNIS collaboration is also considering a different detector design, based on 2 kton of Lead perchlorate, with a high sensitivity to ν_e too. Experiments based on neutron spallation reactions require a neutron poor environment; recent measurements seem to indicate the Carlsbad (New Mexico) site as a promising one [CLI99].

LANNDD

LANNDD (**L**iquid **A**rgon **N**eutrino and **N**ucleon **D**ecay **D**etector) is a proposal of a 70 kton magnetized Liquid Argon tracking detector. In case of a galactic supernova this detector should observe ~ 3000 ν_e CC reactions (13) [CLI01].

IceCube

IceCube is a project of a 1 Km^3 volume neutrino telescope, to be located at the South Pole, designed for the detection of extremely high energy neutrinos ($\gtrsim 10^{20}$ eV) of astrophysical origin. This experiment should be equipped with a supernova trigger of the AMANDA type, with improved sensitivity due to the larger (4800) number of OMs. IceCube should be able to identify the leading front of the supernova neutrino signal with a $\lesssim 3$ ms absolute timing accuracy, instead of the 15 ms AMANDA accuracy. This number looks promising from the point of view of supernova direction reconstruction by the triangulation method (see section 5.3) [GOL01].

5 What can we learn ?

A complete review of all that might be learned from a supernova explosion would require the time and space of a very long report; then I shall limit myself to few points.

5.1 Determination of supernova and neutrino parameters

The large neutrino burst that is expected from a galactic supernova should allow the extraction of some parameters of the supernova source and of the neutrino signal. Here I do not discuss how these determinations are affected by possible neutrino oscillations; this point will be examined in section 5.4.

Present detectors (expecially SK) should record thousands of (7) events; this will allow a high accuracy measurement of the $\bar{\nu}_e$ spectrum and time profile. A simple fit with trial spectra to these data should provide the $\bar{\nu}_e$ temperature $T_{\bar{\nu}_e}$ and chemical potential $\mu_{\bar{\nu}_e}$ with a 1 % accuracy. A lower accuracy (~ 10 %) measurement should be possible also for ν_e, via CC (p.e. on Deuterium) and ES reactions. The total emitted energy E_B could also be measured, since it is related to the total number of events in both flavours and to the supernova distance D; the two independent measurements of E_B/D^2 (the source strength at the detector) could be compared to check whether the energy equipartition hypothesis holds.

The extraction of T_{ν_x} is more complicated, since the NC reactions do not preserve any information on the neutrino energy. However, if one assumes the energy equipartition, an estimation of T_{ν_x} will be obtained by comparing the observed number of events with that predicted from a supernova of the measured E_B/D^2. Note that any separation between ν_μ or ν_τ is forbidden by the nature of the detection process (the NC reactions are insensitive to the flavour). The rough estimation of T_{ν_x} will also allow to test the temperature hierarchy: $T_{\nu_x} > T_{\bar{\nu}_e} > T_{\nu_e}$.

Note that the energy spectrum and the total number of events are not affected by a (possible) finite neutrino mass; then, the temperature and source strength determinations discussed above are valid for massless and for massive neutrinos too. Only in case of a "large" ($\sim$ some KeV) neutrino mass a potential problem is present: since the neutrino signal would be largely broadened, some events could become indistinguishable from the time-independent background and would be lost. This would produce an underestimation of the total number of events and then a normalization problem.

5.2 Fast supernova observation: the SuperNova Early Warning System (SNEWS)

The astrophysical models predict, as confirmed by the SN1987A observation, that the neutrino signal preceeds the supernova optical flare by some hours, the time needed to the shock wave to propagate through the collapsed matter and to the optical light to reach observable magnitudes. Astronomers are very interested in observing the first light from a supernova (not easy to do in case of an extragalactic supernova); this light carries information on the supernova progenitor and its immediate environment. So, many experiments developed systems for prompt recognitions of neutrino bursts from supernovæ.

All these systems are based on the pulsed character of the supernova neutrino signal: given the normal trigger rate of an experiment (due to the environmental and

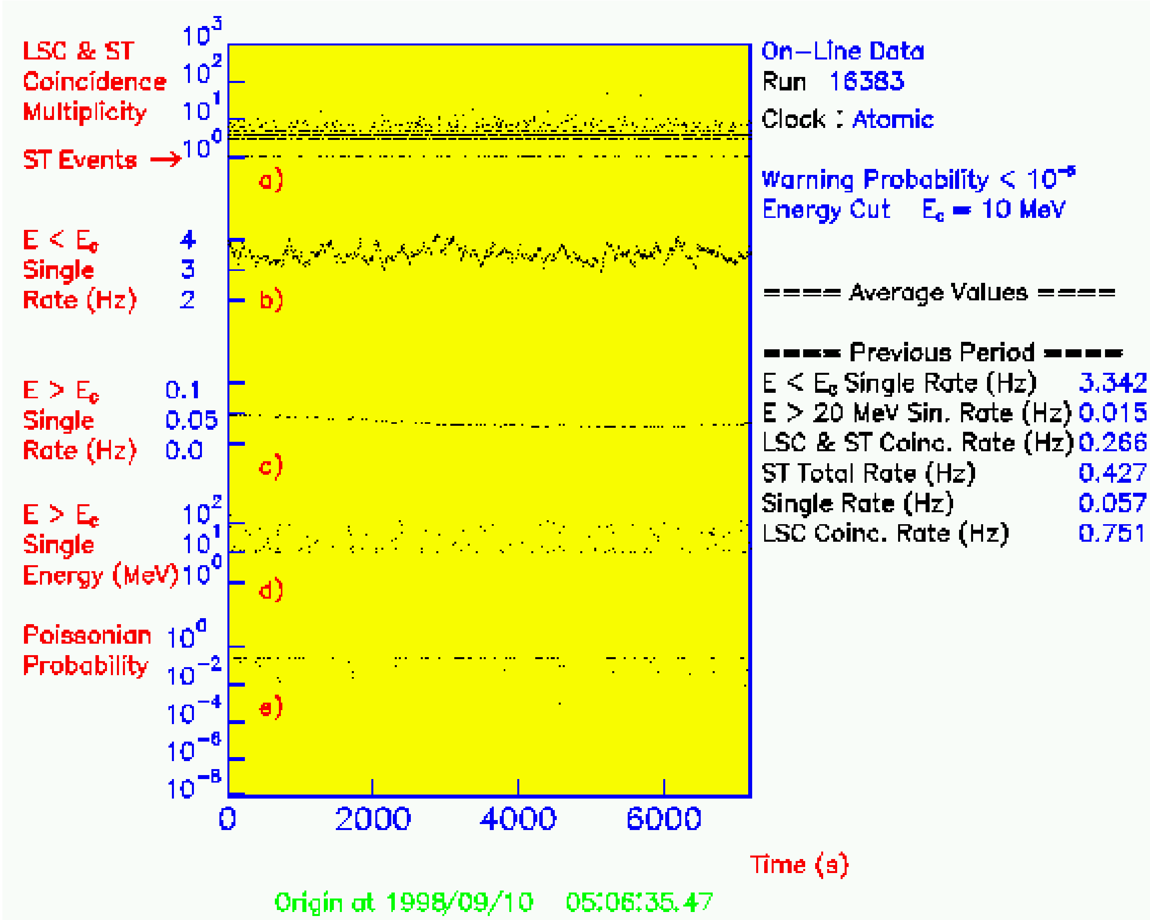

Figure 9: Display of the supernova monitor program of the MACRO experiment (from [MAC98a]).

cosmic background), a neutrino burst should produce a fast increase of this trigger rate, well above any poissonian statistical fluctuation. If such a signal is observed, a second level analysis is performed to recognize whether it matches the expected characteristics for a genuine neutrino burst. Fig. 9 shows the display of the supernova monitor program which was running in the MACRO experiment. A possible burst was signalled by a very low probability of poissonian fluctuations of the background rate (the last scale from above). In the other scales the behaviour of the apparatus was monitored, looking at physical quantities as the energy of the events observed in the scintillation counters. Similar systems are operating in SK, LVD, SNO and AMANDA.

All these systems are members of a coordinate network of supernova observatories (the **SNEWS**, **S**upernova **N**etwork **E**arly **W**arning **S**ystem), whose goal is to provide a fast alert to the astronomical observatories around the world. This system is based on a blind computer, which gets separate alerts from any participating experiment and looks for possible time coincidences, in a 10 s window, between such alerts. This procedure eliminates the human interventions needed to check the supernova-like nature of the burst (which produces a significant loss of time for observation) and ensures a very high level of confidence, since an accidental coincidence of fake supernova bursts (due to poissonian fluctuations or detector pathologies) between different experiments at distances of thousands of Km is extremely unlike [SCH99]. The SNEWS setup is shown in Fig. 10. The estimated response time of SNEWS is few tenths of minutes.

5.3 Identification of supernova direction

The prompt recognition of a supernova burst is not the unique information that supernova neutrino detectors should provide to astronomical observatories, since it is not easy to find something in the sky without any guess on where to look. The pointing back to the supernova is possible with two different techniques: the angular distributions of some neutrino detection reactions and the

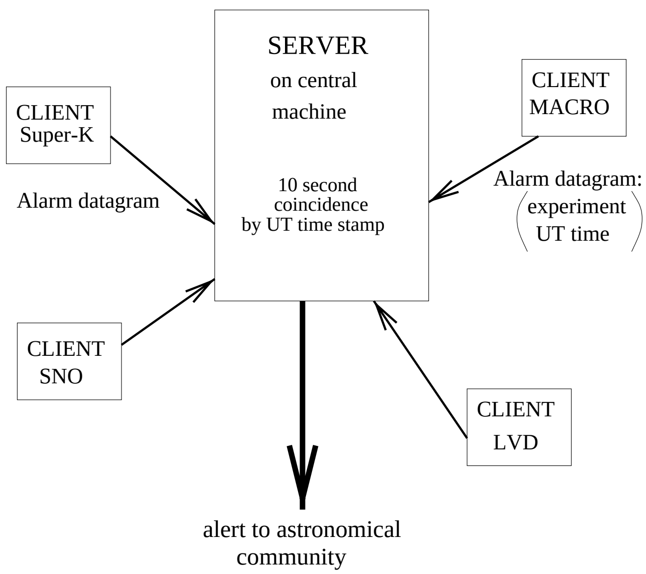

Figure 10: The SNEWS setup (from [SCH99]).

triangulation, which takes advantage from the presence of SNEWS.

Angular distributions.

The most promising reaction for this purpose is the ES (9) process. The extensive discussion [BEA99a] shows that, with some hundreds of ES events, SK should be able to identify the supernova direction with a $\delta\theta \approx 5^\circ$ accuracy for a collapse at the Galactic Center. The accuracy is determined by the intrinsic angle between the recoil electron and the incident neutrino, by the width of the Čerenkov cone, by the multiple scattering of the electrons in water and by the uncertainties introduced by the statistical separation of the ES events from the dominant (7) signal. The result is given under very pessimistic assumptions on the separation capabilities; using more refined techniques this accuracy can be improved down to $3 \div 4^\circ$. A lower accuracy (due to the limited statistics) localization can be obtained in Sudbury: $\delta\theta \approx 20^\circ$. These results are largely independent from the details of the supernova model and particularly of the time evolution of the neutrino luminosity.

The angular distributions of the (7) process and of the CC reactions on Oxygen and Deuterium can provide information at a lower level, but they can be used as a check of the higher accuracy results based on ES reactions to confirme, at least, the sky emisphere where to look.

As observed before, scintillation detectors are sensitive to $\gamma_{2.2}$, while water Čerenkov experiments are not. This opens to the scintillation detectors an other opportunity to provide information on the supernova direction. The positron is detected nearly at the point of creation, while the neutron is boosted forward. The neutron thermalization (dominated by elastic scatterings on protons) preserves the initial direction in the first collisions and then becomes isotropic. The $\gamma_{2.2}$ emission is an isotropic process and the $\gamma_{2.2}$ position is reconstructed with uncertainties of few tenths of cm; these degrading effects reduce the significance of the initially forward motion, but do not completely destroy the memory of it. As a result, the reconstructed point of neutron capture is, on the average, displaced by a small amount with respect to the positron position. The average displacement is few cm, a difference which can be measured because of the good localization capabilities of the liquid scintillation detectors. The CHOOZ experiment [CHO00a] measured a 1.5 cm average displacement for low energy ($E \lesssim 8$ MeV) $\bar{\nu}_e$'s from a nuclear reactor and the reactor direction was reconstructed, using this technique, with a 18° accuracy. At supernova neutrino energies the higher kinetic energy of the neutron and the lower neutron-proton cross section should enhance the effect. The CHOOZ collaboration estimated that a liquid scintillation detector with a mass like that of SK would reach a 9° pointing accuracy, a result worse within a factor 2 than that obtainable using ES events.

Triangulation

The triangulation technique uses the difference in arrival times of neutrino signals in various detectors around the world to determine the supernova direction. If Δt is the difference in arrival time of the signals and d is the physical distance between two detectors (in time units, $d \approx 40$ ms for detectors located on the opposite sides of the earth), the angle θ between the axis connecting the experiments and the supernova direction is given by:

$$\cos\theta = \frac{\Delta t}{d} \tag{15}$$

The uncertainty of this technique is dominated by the uncertainty in measuring Δt, which is related to the capabilities of the two experiments of timing the leading edge of the neutrino signal. The accuracy obtainable for a collapse at the Galactic Center using a triangulation between SK and SNO ($d \approx 30$ ms) is evaluated in [BEA99b] under reasonable and under extreme assumptions on the event time profile (note that a high statistics detector like SK could measure this time profile in detail). The lower statistics of the SNO signal determines a maximum accuracy $\delta(\Delta t) \approx 15$ ms, so that the best obtainable accuracy on the cosine of the angle is $\delta(\cos\theta) \approx 0.5$ (0.25 only in the unrealistic hypothesis of a zero rise-time signal). If one considers triangulations between SK, SNO and one of the other present detectors (e.g. LVD or AMANDA) there are no substantial advantages, since the uncertainties in timing the start of the neutrino signal for these experiments are at the level of that of SNO. An important improvement is expected from the application of the triangulation technique to (possible) future detectors, with higher statistics and sensitivity. For example, a three detectors triangulation involving SK, SNO and IceCube should locate the supernova direction with an uncertainty varying from 5° to 20° [NEU01].

5.4 Non-standard neutrino physics with supernovæ

A galactic supernova would provide a unique opportunity for searching for non standard model properties of neutrinos. Here I discuss how a supernova neutrino signal can give important insights on neutrino masses and oscillations.

ν_e mass

The present $\bar{\nu}_e$ mass limit, obtained by Tritium β-decay experiments, is ≈ 3 eV ([WEI99], [LOB99]). In case of a galactic supernova at a distance D, a massive neutrino of energy E should arrive on the earth with a delay:

$$\Delta t\,(E,m)\;(s) = 0.515 \left(\frac{m\,(\mathrm{eV})}{E\,(\mathrm{MeV})}\right)^2 D\,(10\ \mathrm{Kpc}) \quad (16)$$

with respect to a massless neutrino emitted by the supernova at the same time. The intrinsic duration of the cooling phase (≈ 10 s) tends to mask the delay induced by a finite neutrino mass and determines the minimum ν_e mass whose effects can be explored by an experiment. In case of SN1987A, model dependent and independent limits were obtained in the range $11 \div 23$ eV (see [BAH89] and references therein). An other more sensitive approach was recently suggested [TOT98b] which, taking advantage from the high statistics expected in present supernova detectors (expecially SK), avoids this problem using the events (~ 300 in SK) observed in a short time window, the first $\sim 50 \div 100$ ms after the explosion. The basic idea is that, in case of massless neutrinos, the neutrino arrival times t_i and energies E_i are essentially uncorrelated, since in a so short time window the energy spectrum does not change significantly. The correlation introduced by a finite neutrino mass (equation (16)) is removed if one considers the modified time sequence ${t_i}' = t_i - \Delta t\,(E_i, m)$. Using groups of trial neutrino masses $m_{\bar{\nu}_e}$ and temperatures $T_{\bar{\nu}_e}$, one can evaluate the degree of uncorrelation between ${t_i}'$ and E_i by statistical methods; the maximum uncorrelation is obtained for the correct values of $m_{\bar{\nu}_e}$ and $T_{\bar{\nu}_e}$. The expected sensitivity of this method is down to 3 eV, at the same level of the present terrestrial limit, and results largely model independent.

ν_μ and ν_τ masses

The terrestrial limits of ν_μ and ν_τ masses (properly speaking, of the predominant mass eigenstates of them) are 170 KeV [ASS96] and 18 MeV [ALE98], hard to significantly improve with usual techniques; however, cosmological bounds suggest [RAF96] that these masses could not exceed tenths of eV. A galactic supernova should produce hundreds of ν_x events in the present detectors. Several ideas were therefore proposed in the past (see e.g. [ACK90], [RYA92]) to set stringent ν_x mass limits using a supernova neutrino burst.

Such techniques are based on the statistical separation of the neutral current signal from the dominant one (7) in detectors (mainly liquid scintillators) sensitive to both. The feasibility of such a separation determines the minimum exploitable ν_x mass; sensitivities down to $100 \div 150$ eV masses were obtained. The maximum exploitable ν_x mass m_{max} is set by the level of the experimental background, since for very high masses the ν_x burst becomes so broad that the average time distance between the events is comparable with the inverse of the normal trigger rate. For present detectors $m_{max} \sim 1 \div 10$ KeV.

Other techniques ([KRA92], [FIO97]), developed for water Čerenkov detectors, use the high directionality of the ES reactions to form two samples of event, one made almost only by ν_e and $\bar{\nu}_e$, the other containing also ν_x-induced events. The first sample is used to perform a statistical subtraction of the irriducible ν_e, $\bar{\nu}_e$ background from the second one; the time profile obtained after this subtraction is affected by a finite neutrino mass. The minimum detectable mass is ~ 50 eV in [KRA92] and > 100 eV in [FIO97], a difference ascribed to the very quickly decaying neutrino luminosity of the model used in the former paper.

A recently proposed technique [BEA98b] enhances the sensitivity to small neutrino masses.

Let us assume that ν_e (and then $\bar{\nu}_e$) are massless, while ν_τ and ν_μ (at least one) are massive. The equation (16) can not be immediately applied to extract m because of the neutrino signal duration and since the ν_x energy is not measured (except that in ES reactions). However, consider two samples of events, one ($R\,(t)$, the "Reference") formed by massless neutrinos only and one formed mainly by massive neutrinos, with some contaminations from massless neutrinos ($S\,(t)$, the "Signal"). The first sample could be extracted by SK (or LVD) $\bar{\nu}_e$ data or by the heavy water portion of the SNO signal and the second by ^{16}O NC reactions in SK, or by NC reactions on Deuterium in SNO etc. The residual contamination (estimated $\sim 20\,\%$) comes from the dominant $\bar{\nu}_e$ signal in the energy interval $5 \div 10$ MeV for SK and from CC reactions on Deuterium for SNO; in both cases, an event-by-event separation is not possible. For each of these samples, one can define an average arrival time ($\langle t_R \rangle$ and $\langle t_S \rangle$) and compare the two values. The signature of a finite ν_x mass is given by a statistically significant difference $\langle t_S \rangle - \langle t_R \rangle > 0$. Fig. 11 shows the results of 10^4 Monte Carlo simulations (each simulation is a supernova) of the difference $\langle t_S \rangle - \langle t_R \rangle$ [BEA98b] in the case of SNO; the supernova distance is taken as 10 Kpc and the samples are generated taking into account the number of events expected in the various detectors. The upper part of the

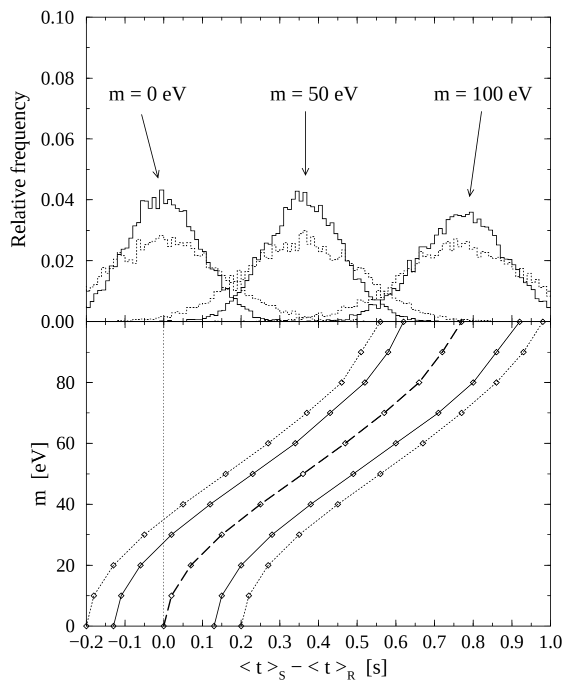

Figure 11: Mass sensitivity analysis for SNO. Upper part: distribution of the time difference $\langle t_S \rangle - \langle t_R \rangle$ for three representative cases. The solid line is for reference time profile extracted from SK data, the dotted line for reference extracted from SNO data. Lower part: the range of masses corresponding to a given measured $\langle t_S \rangle - \langle t_R \rangle$. The dashed line is the corresponding central value; the continuous lines are $10\,\%$ and $90\,\%$ C.L. limits obtained using the SK $R\,(t)$ and the dotted lines are the same using the SNO $R\,(t)$ (from [BEA98b]).

plot shows the distribution of the difference $\langle t_S \rangle - \langle t_R \rangle$ for three representative cases ($m = 0$, 50, 100 eV); the distributions are narrower if the reference signal $R\,(t)$ is taken from the larger statistics sample provided by SK and wider if, instead, $R\,(t)$ is extracted from the SNO data. The lower part is a sort of "reverse" plot: given a measured $\langle t_S \rangle - \langle t_R \rangle$ difference, the thick dashed line defines the corresponding central ν_x mass value, while the continuous lines define the $10\,\%$ and $90\,\%$ C.L. limits obtained using SK data for $R\,(t)$; the dotted lines are the same if one uses the SNO data for $R\,(t)$. This figure shows that the SNO sensitivity is expected to reach ~ 30 eV, a six orders-of-magnitude improvement for the ν_τ mass limit.

Similar analyses performed for other detectors predict sensitivities down to 50 eV for SK, 55 eV for Kamland and 75 eV for Borexino ([BEA99b], [CAD00]); all these results are obtained assuming that only ν_τ is massive. However, the claimed evidence of atmospheric neutrino oscillations seems to suggest an almost total mixing between ν_μ and ν_τ [SKA98b]; if this is the case, the quoted sensitivities improve by a factor $\sqrt{2}$.

The results discussed here are largely independent from the supernova distance (within our galaxy) since the smaller delay is compensated by the increased statistics. Note that this technique uses the large $\bar{\nu}_e$ signal as an internal clock; this makes the results less dependent on the model, since it does not require theoretical assumptions on the time pattern of the neutrino signal, except that the cooling phase duration is ~ 10 s, as observed for SN1987A. A much longer (hundreds of seconds or more) cooling phase would make the analysis more complicated and less sensitive, since the experimental background might not be neglected, as implicitly assumed.

The potentialities of the proposed NC sensitive detectors based on heavy nuclei (SNBO/OMNIS and LAND) for the ν_x mass measurement were also discussed ([CLI94], [SMI97]). The ν_x mass value should be inferred from the distorsions of the observed time profile from that predicted for a massless particle (the neutrino massless time profile is measurable with high accuracy by SK); sensitivities down to few tenths of eV are claimed.

Even better sensitivities could be obtained in the particular case of a supernova which rapidly degenerates into a black hole [BEA00]. In this case the neutrino signal would terminate abruptly at the black hole formation time t_{BH}, with an expected transition of $\lesssim 0.5$ ms duration. In case of a finite neutrino mass, the drop in luminosity would be steeper for higher energy neutrinos and smoother for lower energy neutrinos; so, a first sample of energetic neutrinos could be used to extract t_{BH} with an accuracy $\lesssim 1$ ms and a second sample of less energetic neutrinos could be used to unfold the neutrino mass value from the tail of the neutrino luminosity at $t > t_{BH}$. The expected sensitivity of this technique for the present detectors is down to 1.8 eV for ν_e and down to 6 eV for ν_x.

Neutrino Oscillations

The supernova spectra discussed in section 2 are based on the hypothesis of massless neutrinos, which do not experience flavour mixing. However, the long-standing solar neutrino problem (for recent reviews of the problem and of the proposed solutions see e.g. [BAH01], [FOG01]) and the positive indications coming from atmospheric neutrino experiments ([SKA98b], [MAC98b], [SOU97]) are strong hints in favour of neutrino oscillations. An unconfirmed indication comes also from the LSND [LSN98] experiment. Such effects could manifest during the collapse (expecially if the MSW ([MIK86], [WOL78]) mechanism works) or during the neutrino travel from the collapsed star to the earth. Note also that a supernova neutrino detection would offer the opportunity to study vacuum oscillations over an unprecedented baseline.

The effects of the neutrino oscillations on the supernova neutrino spectra and their signatures in terrestrial detectors were discussed by many authors (see e.g. [FUL87], [BUR92], [RAF93], [BUR93], [QIA94], [FUL99], [CHO00b]), using a large variety of mixing parameters (mass squared differences and mixing angles). The neutrino oscillations, for instance, were advocated as a strengthening effect for the shock wave neutrino heating [FUL92] and the request of an efficient r-process nucleosynthesis in the supernova core was used as an argument to set bounds on neutrino mixing parameters [QIA93].

The combination of the results of all neutrino oscillation experiments restricts (at 99 % C.L.) the possible solutions of the solar neutrino puzzle to four regions of the $\left(\Delta m^2, \sin^2 2\theta\right)$ plane, the vacuum (**VO**) oscillation and the three (**LMA**, **SMA** and **LOW**) resonant MSW conversions (the first one is presently the favoured). Each of them is characterized by a different couple of parameters $\left(\Delta m^2_{\odot}, \sin^2 2\theta_{\odot}\right)$:

- $\left((4 \div 10) \cdot 10^{-6}\ \mathrm{eV}^2, (2 \div 10) \cdot 10^{-3}\right)$ for SMA;
- $\left((1 \div 10) \cdot 10^{-5}\ \mathrm{eV}^2, (0.7 \div 0.95)\right)$ for LMA;
- $\left((0.5 \div 2) \cdot 10^{-7}\ \mathrm{eV}^2, (0.9 \div 1.0)\right)$ for LOW;
- $\left((6 \div 60) \cdot 10^{-11}\ \mathrm{eV}^2, (0.8 \div 1.0)\right)$ for VO.

The electron flavour is distributed in the mass eigenstates ν_1 and ν_2, with admixtures given by $U_{e1} \approx \cos\theta_{\odot}$, $U_{e2} \approx \sin\theta_{\odot}$. The admixture U_{e3} of the electron with the third neutrino mass state is unknown, but is strongly bounded by the CHOOZ result [CHO99]: $|U_{e3}|^2 \lesssim 0.02$. The atmospheric neutrino anomaly favours the hypothesis of oscillation between two active neutrino states ("2" and "3"), usually identified with ν_μ and ν_τ; the corresponding pair of parameters is $\left(\Delta m^2_{atm}, \sin^2 2\theta_{\mu,\tau}\right)$. The almost complete degeneracy between the states is expressed by the condition: $\sin^2 2\theta_{\mu,\tau} > 0.88$ and the favoured Δm^2_{atm} value lies in the range $(1.5 \div 4) \cdot 10^{-3}\ \mathrm{eV}^2$.

Having these parameters in mind, some general results can be inferred [DIG00]:

- in the supernova, where the density reaches 10^{14} g cm^{-3}, two different MSW resonances occur. Independently of the solar neutrino problem solution, these resonances take place in the mantel, without affecting the explosion dynamics and expecially the shock neutrino heating. This happens because during the 10 s of the diffusion process the shock wave reaches regions where the density is $\gtrsim 10^6$ g cm^{-3}, while the maximum density for a MSW resonance is $\lesssim 10^4$ g cm^{-3};
- the nucleosynthesis is also unaffected, since $\Delta m^2_{\odot}$ (which determines the ν_e mixing) is much lower than the nucleosynthesis upper bound;
- since the MSW effect is sensitive to the sign of Δm^2, only ν_e (in case of normal mass hierarchy) or $\bar{\nu}_e$ (in case of inverted mass hierarchy) can experience a resonant conversion, but not both;
- the earth matter effects must also be taken into account, since in ~ 60 % of all possible neutrino arrival times the neutrinos cross a substantial amount of terrestrial matter before reaching at least one of the existing detectors [LUN01].

The neutrino energy spectra measured by the various detectors (one can take as representatives SK, SNO and LVD) are the main tool to draw conclusions about neutrino oscillations, since the ν_e, $\bar{\nu}_e$ and ν_x spectra will be distorted with respect to the no mixing case, with a degree of distorsion strongly dependent on the type of mixing mechanism.

The ν_e neutronization peak can be completely destroyed by an efficient conversion; this would be signalled by the comparison of ν_x events in the first 10 ms. In this case one should expect a hard ν_e spectrum in the cooling phase, coming from $\nu_x \to \nu_e$ oscillations. These two features come together and are realyzed for all solar neutrino solutions with normal mass hierarchy, provided that the $|U_{e3}|^2$ parameter is such that only adiabatic conversions occur. The $\bar{\nu}_e$ spectrum becomes in this case crucial to distinguish between the various solutions: if it is not affected, the SMA solution is singled out, while if it exhibits distorsions, with some hardening effects, the LMA, LOW or VO solutions are possible. A careful analysis of the earth matter-induced distorsions of $\bar{\nu}_e$ spectra could allow to perform the final distinction.

If, on the other hand, the ν_e neutronization peak is made by ν_e and ν_x, the ν_e spectrum in the cooling phase has also a "soft" (due to the uncoverted ν_e's) and a "hard" (due to the converted ν_x's) component. These two components would give rise to observable distorsions, the most obvious of them being the presence of ν_e events at energies above the expectations, i.e. a broadening of the ν_e energy spectrum. Only the SMA solution is possible in this case if the $\bar{\nu}_e$ spectrum exhibits no distorsions. Note that the supernova models predict a higher energy tail for $\bar{\nu}_e$ than for ν_e; the scenario described above could produce an inverted situation.

If both the ν_e and $\bar{\nu}_e$ spectra have a "soft" and a "hard" component, the situation is more complicated, since this scenario can be realized in many cases. However, earth-matter effects could help because they would be present for ν_e and $\bar{\nu}_e$ in case of LMA solution, present only for ν_e in case of SMA solution and completely absent in case of VO solution. Fig. 12 shows the earth-matter effects on the ν_e and $\bar{\nu}_e$ spectra for some representative cases.

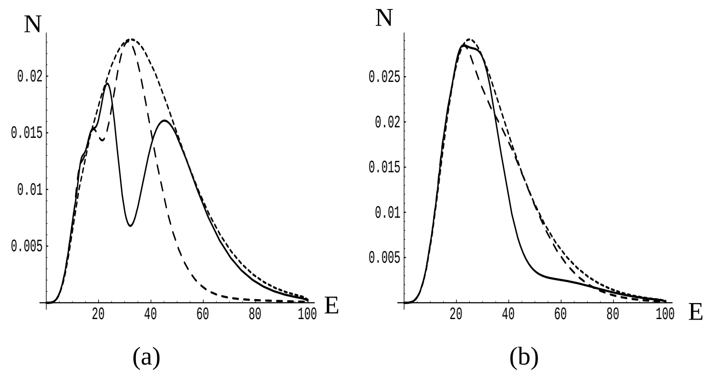

Figure 12: The earth matter effects on the ν_e (a) and $\bar{\nu}_e$ (b) spectra in a scenario with LMA solution. The dotted, dashed and solid lines show the spectra of the normalized number of CCN events when the distance travelled by neutrinos through the earth is 0, 4000 and 6000 Km respectively (from [DIG00]).

Finally, a ν_e spectrum with a "hard" and a "soft" component and a $\bar{\nu}_e$ spectrum with only the "hard" component are obtained only with an inverted mass hierarchy and a $|U_{e3}|^2$ value which makes possible only adiabatic conversions, whatever is the solar neutrino problem solution (LMA, SMA, LOW or VO). If one of the resonant conversions is the true mechanism, earth effects on the ν_e spectrum should be observable.

Obviously, if the oscillation parameters are not in the selected range one could have different effects, for instance a pure ν_e neutronization burst, which could definitely rule out the examined scenarios (presently the most plausible ones when all experimental data are taken into account). Other scenarios were also studied, for instance using sterile neutrinos to explain the atmospheric neutrino problem (this hypothesis is heavily disfavoured by SK [HAB01] and MACRO [MAC01] data) and a large ($\sim 1 \div 100$ eV), cosmologically significant mass for the heavier neutrino state [CHO00b]. The most significant variable to validate or refuse this scenario is the time behaviour of the ratio between charged and neutral current reactions (e.g. in SNO), since oscillations of higher energy ν_x into ν_e (or $\bar{\nu}_e$) would enlarge the number of CCN reactions without effects on NC reactions.

The general conclusion which can be drawn is that the analysis of the supernova neutrino spectra could help to solve the solar neutrino problem (see also [TAK01]), establish whether the mass hierarchy is normal or inverted and set more stringent limits on the value of $|U_{e3}|^2$.

Note that, as already observed, the supernova neutrino detectors can not give any direct information on the ν_μ-ν_τ mixing, since ν_μ and ν_τ-induced events can not be distinguished.

The determination of neutrino and supernova parameters discussed in section 5.1 would be affected by neutrino oscillations. In case of a strong mixing between ν_e ($\bar{\nu}_e$) and ν_x ($\bar{\nu}_x$) one should observe a T_{ν_e} ($T_{\bar{\nu}_e}$) of ~ 8 MeV, instead of $\sim 3 \div 4$ MeV in case of no mixing; on the other hand, if the mixing is intermediate a double peak structure should appear, produced by the superimposition of the "soft" and "hard" components. Since the number of CC reactions is increased by harder ν_e or $\bar{\nu}_e$ spectra, the normalization (and then the determination of the source strength E_B/D^2) will also be affected. Nevertheless, the fact that in case of MSW resonances only one between ν_e and $\bar{\nu}_e$ experiences resonant conversions would be helpful in disentangling the effects of neutrino oscillations.

5.5 *Combined observations of neutrino bursts and gravitational waves*

Supernovæ are expected to emit not only neutrinos and light of various frequencies, but gravitational waves too (see e.g. [SCH00]). The properties (amplitude, waveform, frequency ...) of the gravitational pulse expected from a supernova are rather uncertain, because they depend on the degree of non-sphericity of the collapse; the expected frequency range goes from $\sim$ 100 Hz to $\sim$ 10 KHz. The detection of the gravitational waves is by itself of enormous importance, since their existence would be the most direct proof of the general relativity hypothesis.

The gravitational waves are even less coupled with matter than the neutrinos; so, they come from the deep interior of the star and do not experience a slow diffusion in the supernova core. Then, a combined observation of neutrinos, gravitational waves and (possibly) light from a supernova would provide a very comprehensive picture of the collapse mechanism, since each of these forms of radiation preserves information on a different region of the stellar structure. Moreover, the gravitational pulse could be used to time the start of the collapse; this opens the possibility to set ν_e mass limits at the level of fractions of eV [ARN01] looking at the time difference between the ν_e neutronization burst and the gravitational waves.

Many gravitational wave detectors of the interferometric (**VIRGO**, **LIGO**, **AIGO** ..) and resonant bar (**EXPLORER**, **NAUTILUS**, **AURIGA**, **ALLEGRO**, **NIOBE** ..) type are on-line or under construction in the world; they will be sensitive to gravitational wave sources well beyond our galaxy. An absolute time resolution of a fraction of ms (fundamental for a good correlation) looks within the reach of such experiments.

The presently operating detectors, all of the bar type, are already sensitive to galactic supernovæ. They form an international collaboration (the **IGEC**, **I**nternational **G**ravitational **E**vent **C**ollaboration), whose aim is to produce a common analysis of available datasets. Note that the bar detectors have a rather narrow frequency band ($\Delta f \sim 50 \div 100$ Hz), with a central frequency (determined by the mechanical inertia of the bar) of ~ 1 KHz, at the center of the frequency range expected for a supernova. (Interferometers are instead wide-band detectors, sensitive to gravitational wave frequencies from few Hz to tenths of KHz.) Efforts are under way to enlarge the resonant bar detector bandwidth. On the other hand, the observation of an optical pulsar with a $T = 2.14$ ms emission period in SN1987A [MID00] (with a modulation well explained by gravitational wave emission) stimulated AURIGA people to try to tune the central frequency of their antenna to the interesting value $f = 1/T = 467.5$ Hz [BEM01].

6 Conclusions

The next galactic supernova will be a huge source of information for astrophysicists and particle physicists. The presence of a composite network of detectors, sensitive (at various levels) to all neutrino flavours will give the opportunity to explore many aspects of the collapse mechanism in large details. Correlations with optical and gravitational wave observations will make this collapse picture even more complete. Astronomers will be helped by the early warning provided by the SNEWS alert system and by the fast localization obtained by the angular distributions of the events and (maybe) by triangulations between various detectors.

At the same time, the particle physicists will have a powerful source of neutrinos of all flavours, with exciting possibilities to set stringent limits on ν_μ, ν_τ masses and on the neutrino oscillation mechanisms. The fact that many of the results discussed here are only weakly model-dependent makes this opportunity even more appealing.

However, a basilar "caveat" is necessary: since there are still many obscure points and a-priori uncertainties in the supernova neutrino emission, the risk of drawing rushed conclusions is just around the corner. Limited statistics and unknown aspects must be carefully taken into account when looking to supernova neutrino data.

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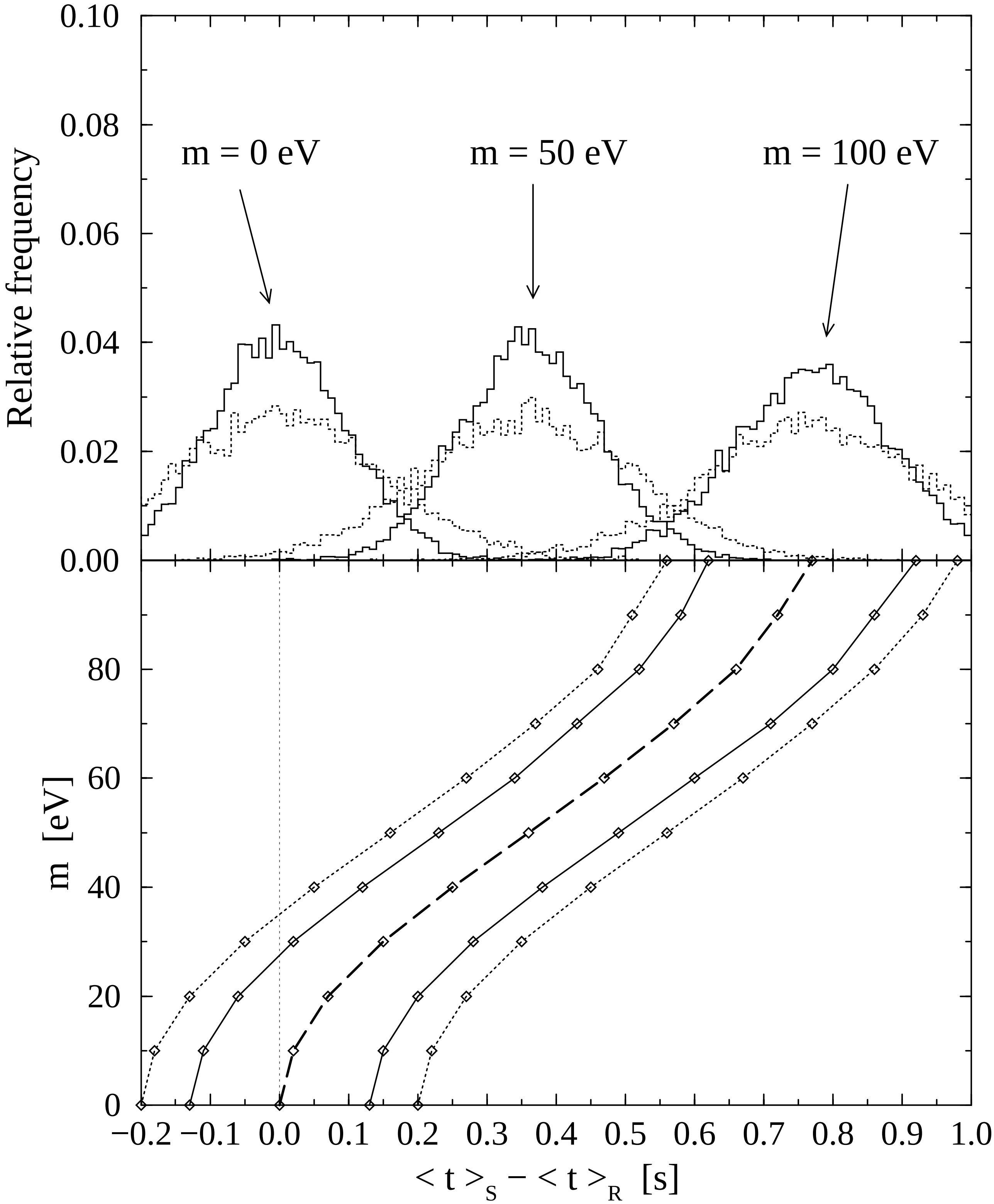

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m = 100 eV
Relative frequency
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0.08
0.06
0.04
0.02
0.00
m [eV]
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60
40
20
0
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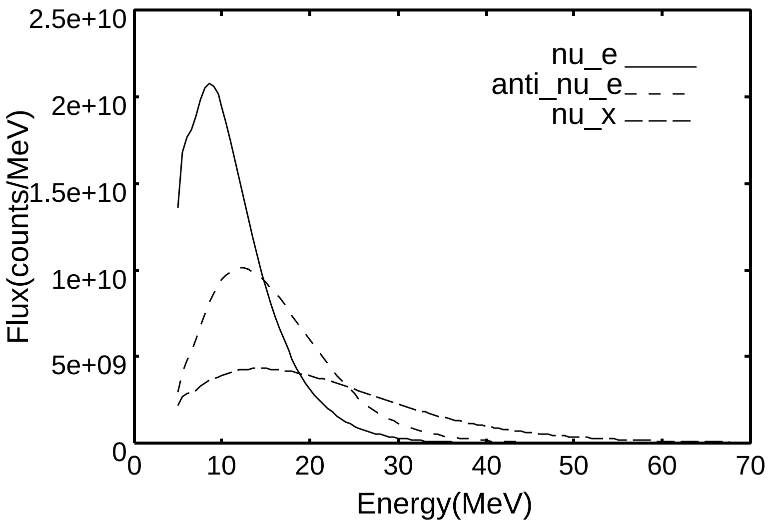

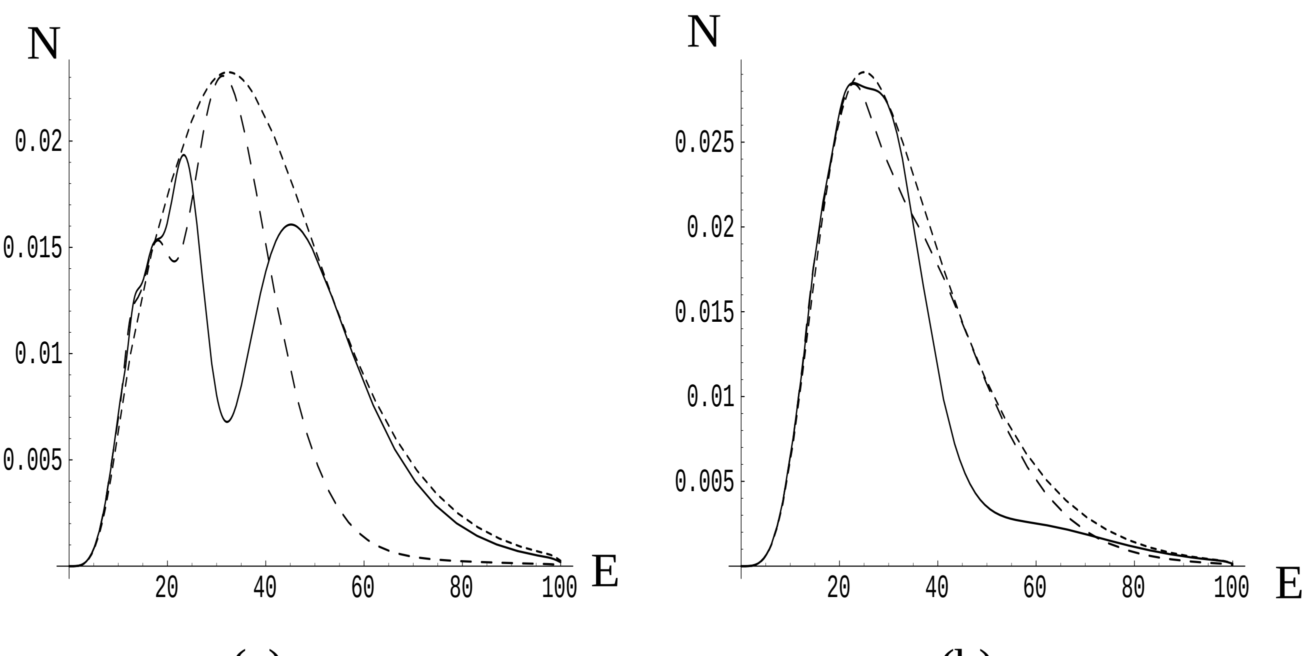

(a)

(b)